Use of GNSS for BEL Determination

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1 Introduction

This document provides the technical foundation for using Global Positioning System/Global Navigation Satellite System (GPS/GNSS) signal loss measurements to estimate a lower bound on indoor to outdoor building loss for CBRS and 6 GHz use cases. It is targeted at measured Building Entry Loss (BEL) as an alternative to stochastic methods such as ITU-P. 2109 [1]. In some cases, the GNSS measurements can provide an estimate of the BEL plus the local clutter loss.

When using stochastic methods, building losses can be estimated to be greater than the actual loss considered to be available between a base device, such as a CBSD or RLAN, and a protected entity, such as a 6 GHz fixed wireless service. There is opportunity to increase base device power while protecting that entity using the measured value. Conversely, when a measured lower bound on the loss is less than the actual value, the measured value can be used to take actions to prevent interference to the protected entity, unlike the stochastic methods where the actual interference can only be determined only after an interference event is experienced.

1.1 Scope

This document focuses on using GPS/GNSS to measure building loss. It provides GPS L1 C/A code and L5 as the measurement signal but can be extended to other GNSS systems as well.

1.2 Abbreviations

3GPP	3rd Generation Partnership Project
AZ	Azimuth
BEL	Building Entry Loss
C/A code	GPS L1 band coarse acquisition code of 1.023 Mchips/sec
CBSD	Citizens Broadband radio Service Device
DPA	Dynamic Protection Area
EL	Elevation
FS	Fixed (microwave) station
FSS	Fixed-Satellite Service
GPS	Global Positioning System
GNSS	Global Navigation Positioning Systems
L1	GNSS frequency band at 1675.42 MHz
L5	GNSS frequency band at 1176.45 MHz
LOS	Line of sight
NIST	National Institute for Standards and Technology
NLOS	Non line of sight
RHCP	Right Hand Circular Polarization

RLAN	Radio Local Area Network (usually device)
Rx	Receiver
SV	Satellite Vehicle
TE	Horizontally polarized wave
TM	Vertically polarized wave
Tx	Transmitter

2 Measurement Background

2.1 Fundamentals

The foundation for using GPS signals to measure the building plus clutter loss, i.e., the site-specific loss, is that the GPS signals are at a known power per location. The power is controlled by the US Air Force to be a minimum of -128.5 dBm into a 0 dBic antenna for L1 C/A code at 1575.42 MHz [6]. Testing has revealed that the power is typically closer to -125 dBm [3] with some measurements as much as 6 dB higher than the minimum reference [2]. Figure 1 shows how this is impinged on a building. The L5 signal at 1176.45 MHz is 4.5 dB higher by design [7] than the L1 minimum code power. Moreover, ground reference stations are used to measure the true power on the ground, and this is relayed to a loss calculation engine which can be in used for a more accurate measurement.

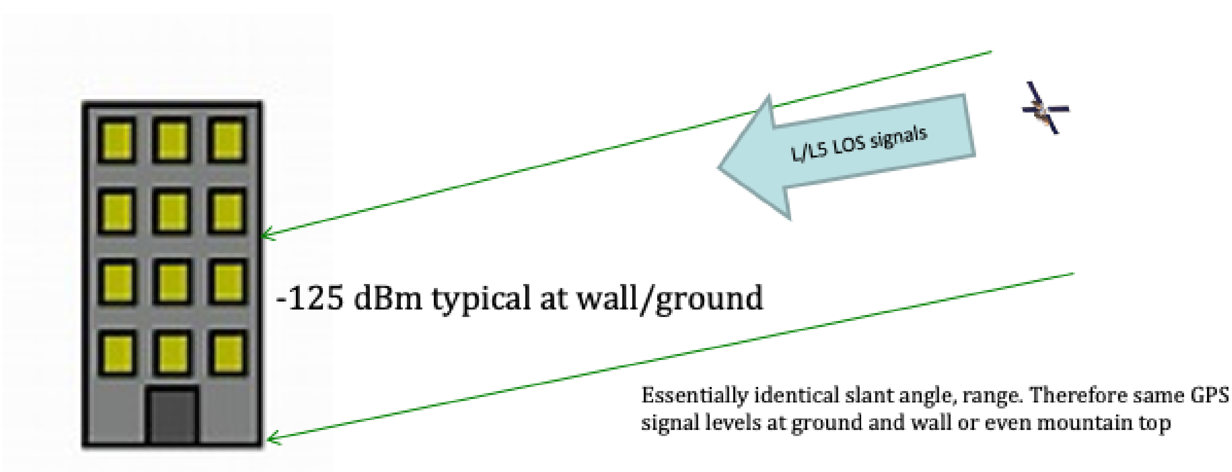

Figure 1: GPS signal at ground and building wall

An exemplary extreme sensitivity receiver using more extensive internet assistance may provide -177 dBm sensitivity. Other alternatively assisted receivers may provide higher sensitivity and different performance.

An analysis of the dynamic range is given below.

GPS typical power	-125 dBm (GPS L1)
	-128.5 dBm guaranteed, [6]
Rx power Sensitivity	-177 dBm
GPS dynamic range	52 dB (-125- -177)
Scale to 3.5 GHz	3.5 dB minimum, 55.5 dB total
Scale to 6 GHz	6 dB minimum , 58.5 dB total

Note: L5 minimum guaranteed power is -124 dBm [7], so has a minimum dynamic range of 57 dB and as much as 4.5 dB more than this using the proper scaling factor as seen in sec. **Error! Reference source not found.**.

2.2 Discussion of BEL Losses due to non-normal incidence a plane wave.

There are two factors that affect the penetration of plane wave signals through materials. They are the reflection coefficient which dictates the power available for penetration after reflection, and the transmission coefficient which dictates the power available after the penetration loss. Reflection analysis at 1575 MHz on 10 cm thick concrete is shown in Figure 2. This closely follows the curves in [1] figure 2.

The analysis on an exemplary concrete material shows that the TM wave (vertical) polarization wave has high surface reflection loss with only an effective power loss due to reflection of 0.75 dB up to about 80 degrees incident/elevation angle as seen in Figure 3. The TE wave (horizontal) polarization has about 2.55 dB more loss at 60 degrees incident angle. Taken together with proper phasing the circular polarization loss is about 1 dB at 60-degree elevation angle.

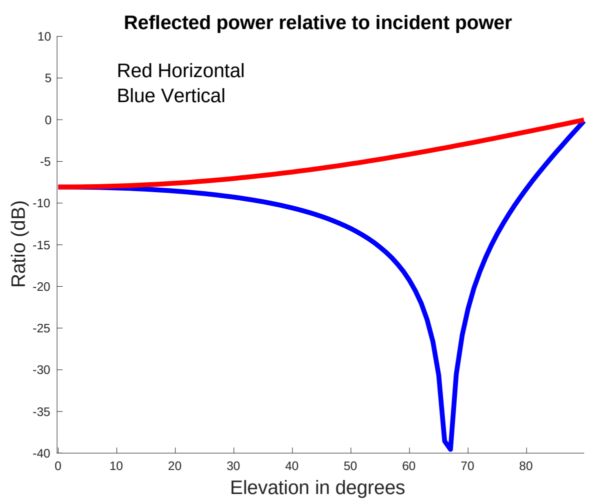

Figure 2: Reflected power for a concrete wall

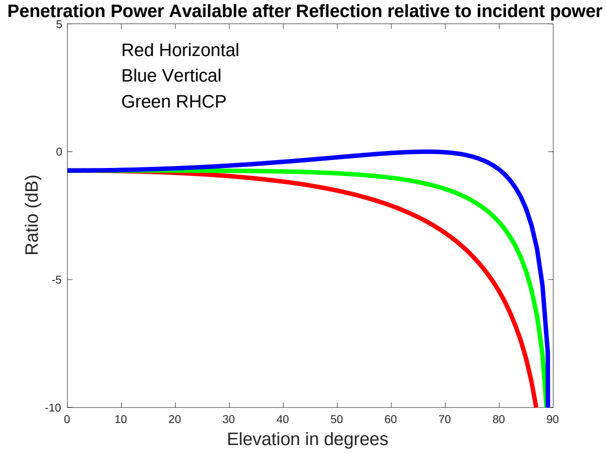

Figure 3: Power available due to reflection to a concrete wall

[1] takes the analysis further as it examines the TM (vertical) and TE (horizontal) reflection and transmission coefficients for different thickness of exemplary concrete at 1 GHz. It's figure 5 shows that the Vertical reflection coefficient is low up to 60 degrees so most of the power remains available for penetration. It's figure 7 shows a negligible difference in transmission loss from 0 to 60 degrees vs material thickness.

[1] figure 4 shows that the horizontal reflection coefficient is low up to about 60 degrees. It also shows that the ripples in loss are not a function of angle which means a measurement at 60 degrees will accurately estimate the loss at 0 degrees although it is a function of thickness. The transmission loss in its figure 6 is constant up to 30 degrees angle and is only 4 dB more loss at 60 degrees than at 0 degrees. Using GPS as a measurement vehicle it uses both components as it is RHCP and will lessen the difference between RHCP and Horizontal and preserves the idea of using GPS for vertical or horizontal signal considerations.

These analyses and measurements represent a single plane wave as is measured in a laboratory such as in [5]. In the real world these values cannot be expected unless the scenario is highly similar to a laboratory with a single ray and no possibility of multipath. There are many rays and entry points into a building which will tend to add to the power meaning the measured loss will be favorably underestimated. This is illustrated in Figure 4.

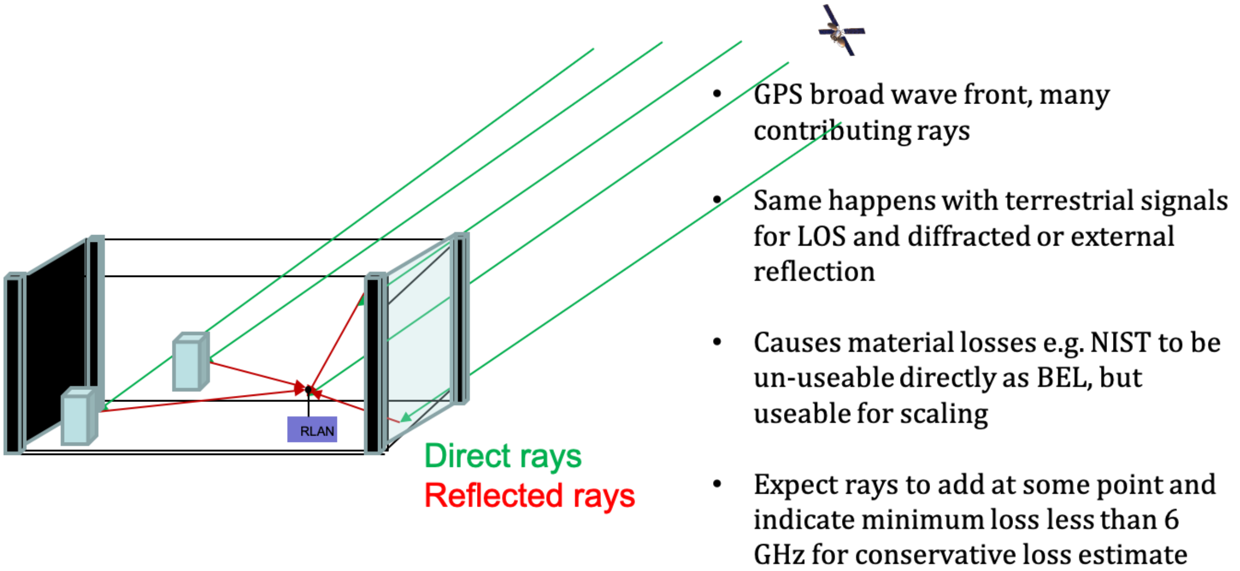

Figure 4: Ray tracing example

BEL measurements using GNSS will contain the true building loss if there is a LOS signal to the building as in Figure 5. An evaluation of the reflection coefficient indicates that the Azimuth (Az) and Elevation angle (El) do not affect the available power for penetration significantly up to about 60 degrees from orthogonal to the building surface [1],[2]. Therefore, the power available for penetration is relatively constant with respect to these angles. In a reciprocal fashion the exiting signal behaves the same as the antennas at both ends are fixed in location and pattern. In this case the measured BEL can be added directly to the path loss model. However, it is best to use measurements at low elevation angles to ensure that the measurement includes any blockage between the transmitting devices and a protected entity like an FSS in the CBRS Band shown in Figure 5 or an RLAN to a FS in the 6 GHz band shown in Figure 6.

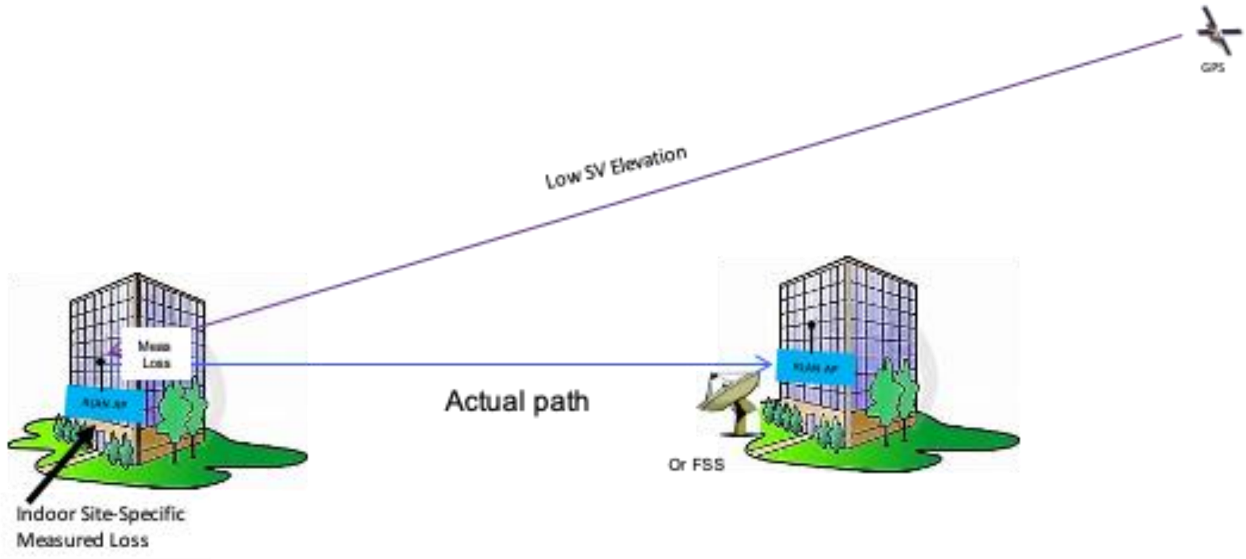

Figure 5: LOS Path from a CBSD to an FSS

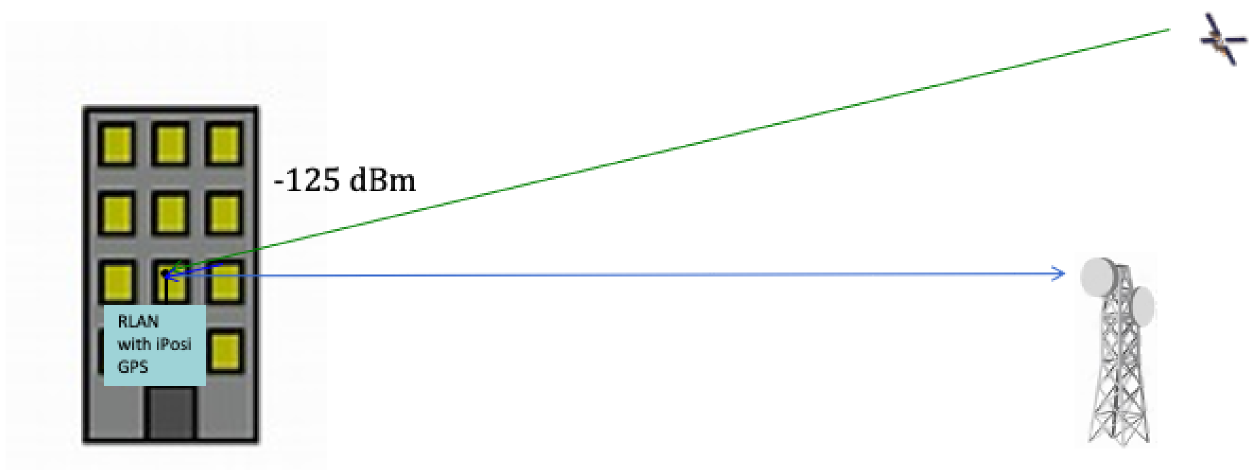

Figure 6: LOS path from an RLAN to an FS

Due to low dependency on Az and El the angle from the transmitting device to the protected entity the angles need not be exact. Rather the minimum loss over a range of elevation and azimuth angles should be used to capture effect of multipath and variable blockage which will preclude the idea of a single value characterizing the BEL. This is also true for terrestrial radio measurements.

In cases where the signal path from the GNSS satellite vehicle (SV) to the base device is blocked, as in Figure 7 for low elevation angles, the BEL will also contain the local clutter. This is typically due to diffraction but may also be due to reflections and scattering. Since the diffraction angle from the SV to the victim is less than the angle from transmitting device to the protected entity, and there are other avenues of SV signal transmission, the measured loss is assured to be less for the SV path, making the measurement conservative for interference calculations. In this case the low elevation angle measurement can be added to the propagation loss model directly.

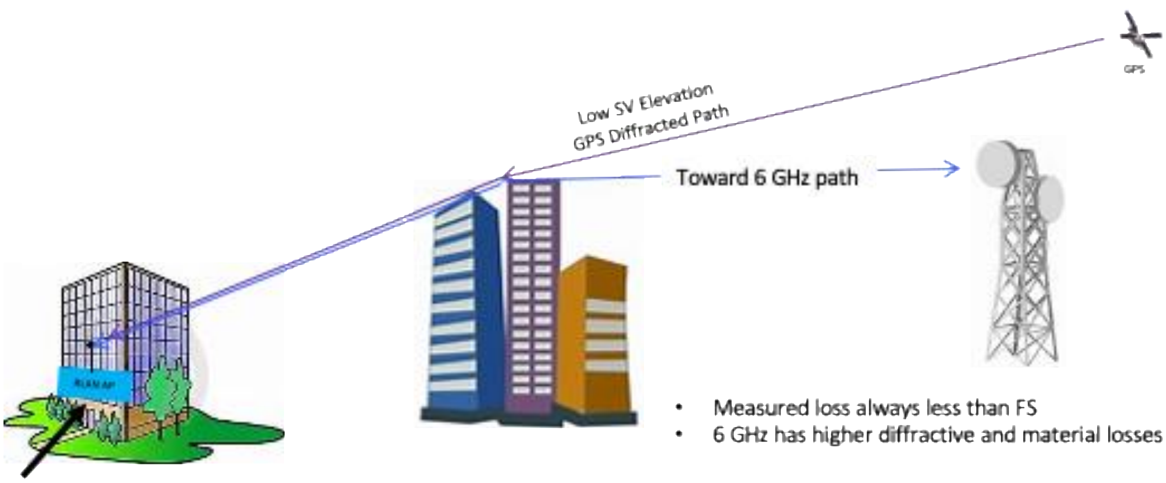

Figure 7: Low elevation NLOS

If true BEL is desired for determination of loss between two adjacent buildings, high elevation angles should be used as seen in Figure 8. This will decrease the likelihood that clutter is included in the loss measurement. The measured value will include reflected and diffracted rays, which will add to the power and provide a conservative loss measurement.

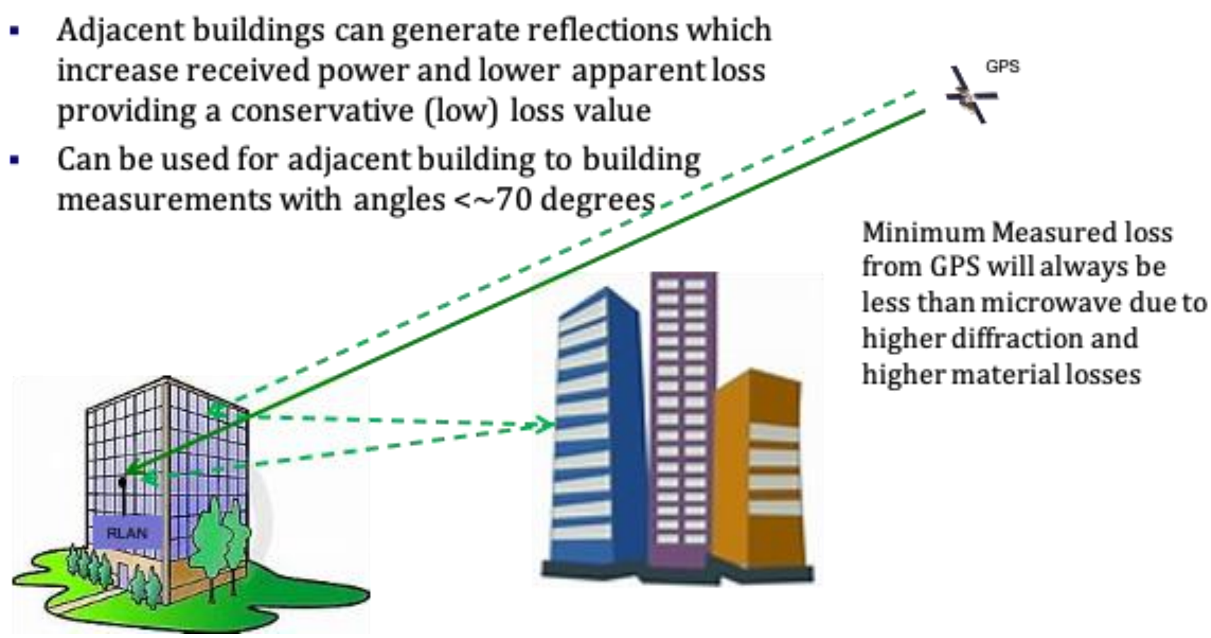

Figure 8: Adjacent building loss measurement

A concern is determining the certainty in measuring the loss from a transmitting device to a protected entity when including clutter, since at low elevation angles there may be clutter which is missed if the SV elevation angle is not low enough. The geometry in Figure 9 was developed to demonstrate the elevation angle versus distance to a 30m high FS antenna from a 10m high RLAN antenna in the 6 GHz band. Inserted is an arbitrary building to illustrate potential blockage and clearance angles in the same Azimuth as the SV.

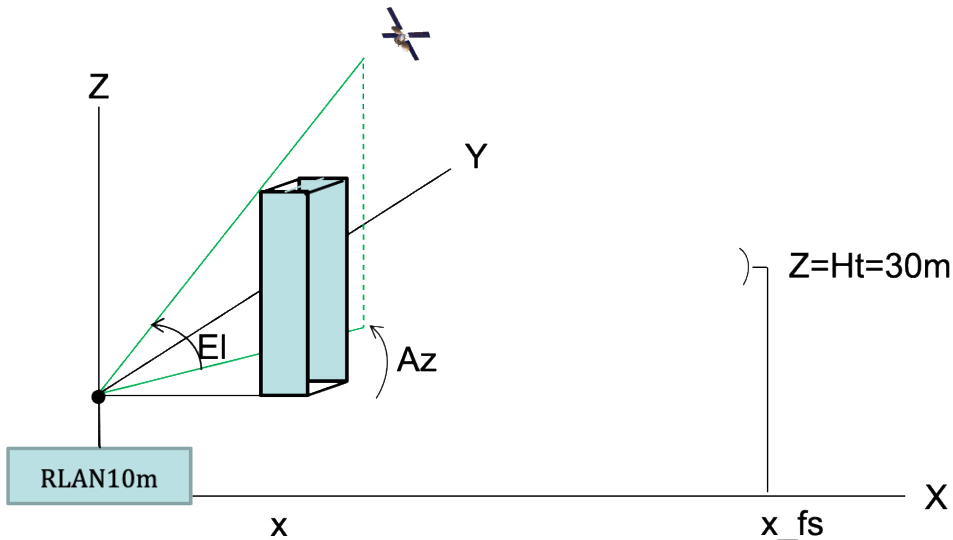

Figure 9: Geometry for Clearance to an SV

Figure 10 shows that for FS =30 m and RLAN =10 m heights, clutter distances up to 200 meters the SV elevation can be 5 degrees, or higher for lower distances, and still capture the local clutter. At higher clutter distances the elevation angle must be lower to capture the clutter. GPS elevation angles less than 5 degrees are possible if a reference receiver is used to measure the SV power on the ground as in Figure 1.For larger distances it is unlikely that the clutter local to the protected entity is significant as the protected entity site designer will be certain there is no clutter between the FS and its partner so communication is assured. This also guarantees that there is no clutter between the SV and the RLAN. This says the nearby clutter in the path of the RLAN and the FS is the significant element and can be measured at 5 degrees up to 200 meters distant from the RLAN in this case. It is important to note that if the FS or the RLAN are higher than 30 and 10 m respectively e.g., FS=100 m and RLAN = 20 m the elevation clearance increases which means it will more likely capture the clutter.

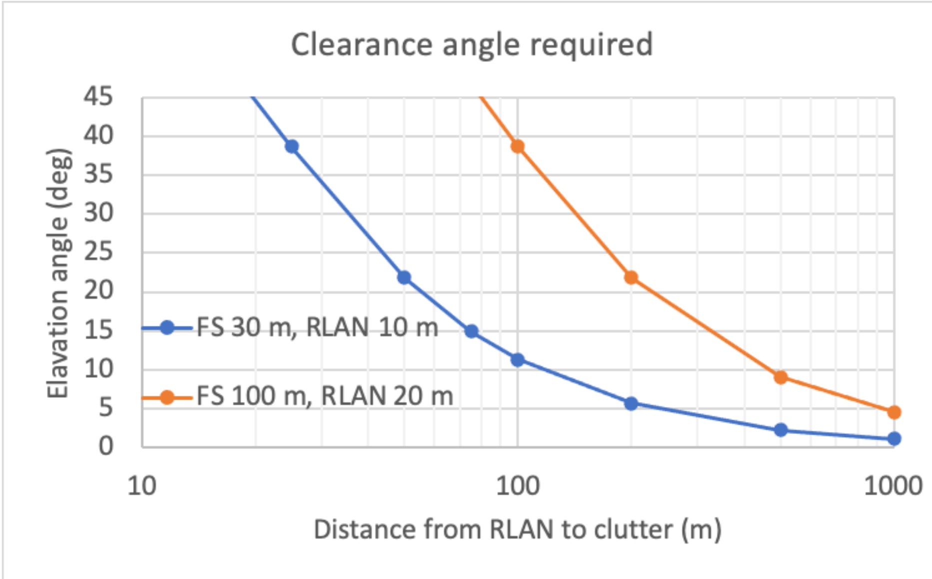

Figure 10: Clearance angle versus distance to clutter

3 Exemplary GPS loss measurement

Figure 11**Error! Reference source not found.** illustrates measurements done on a 7-story building in South Korea in the basement near the southwest wall with no windows. The top left figure shows variability of loss versus elevation with azimuth angle from 20 dB to 40 dB. The second figure shows higher loss consistent with high elevation and azimuth angles with much more building material to pass through plus local scattering.

Figure 11: Measurements of a 7 story Urban Building in the basement

4 Use case 1: CBRS

4.1 L1 scaling

The measured loss at GNSS L1 and L5 frequencies can be scaled to 3.5 GHz using the data provided by NIST in [5]. The data was analyzed for absolute loss and for the relative loss from L1 or L5 to 3.5 GHz. Figure 12 gives a comparison of all the materials measured by NIST excluding very low loss material for L1 and 3.5 GHz. This is because these materials will bias the difference to zero although they are rarely if ever used for construction.

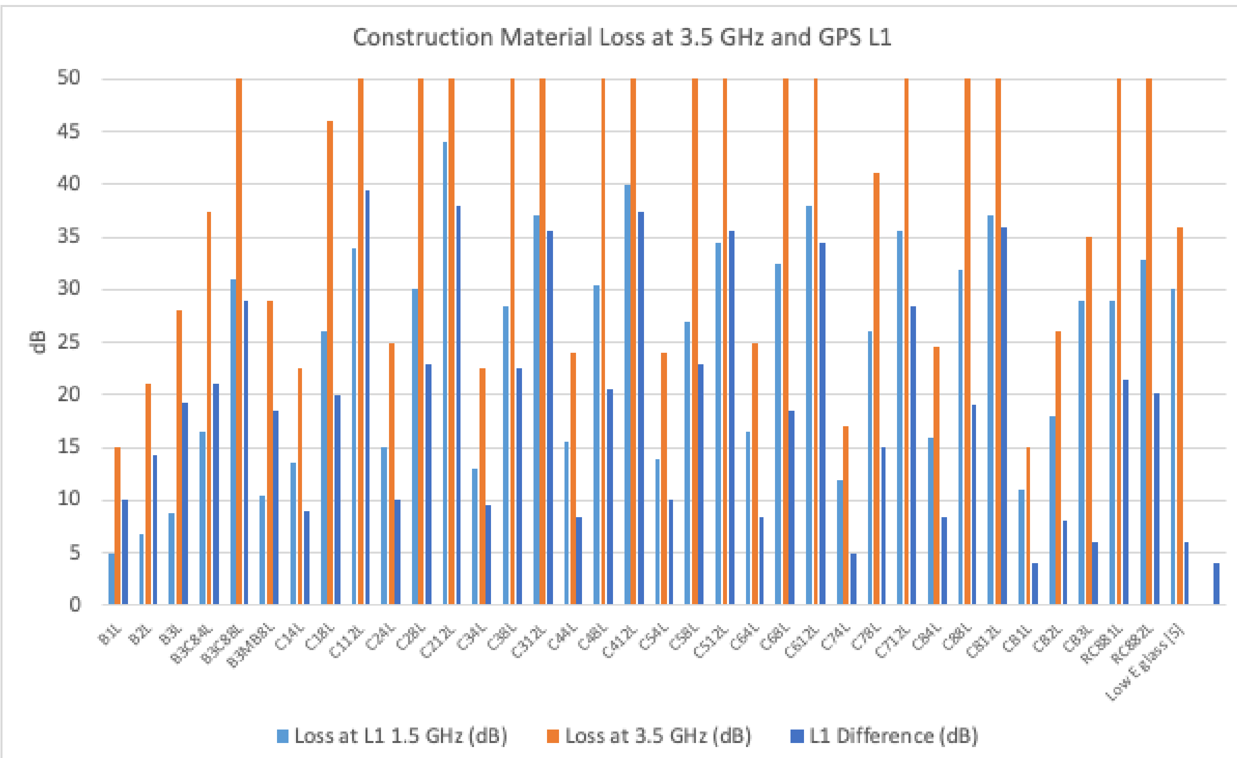

Figure 12: Material losses at 1.575 GNSS L1 and 3.5 GHz. This figure excludes plywood, lumber, standard glass and drywall as these are < 4 dB delta and the L1 and GPS losses are near 0 dB

The important value is the difference from GPS L1 or L5 to 3.5 GHz as seen in Figure 13 and Figure 14. This is for all materials. For low GPS measured loss, the loss at 3.5 GHz is also very low, so the difference is negligible. However, when the GPS L1 loss is greater than 4.4 dB the difference is at least 3.5 dB. This provides guidance on how to use the scaling. Specifically, if the GPS L1 loss is >= 4.5(4.4) dB, 3.5 dB can be added to it to provide an estimate at 3.6 GHz. If one were to choose a different threshold then the scale factor would be different accordingly.

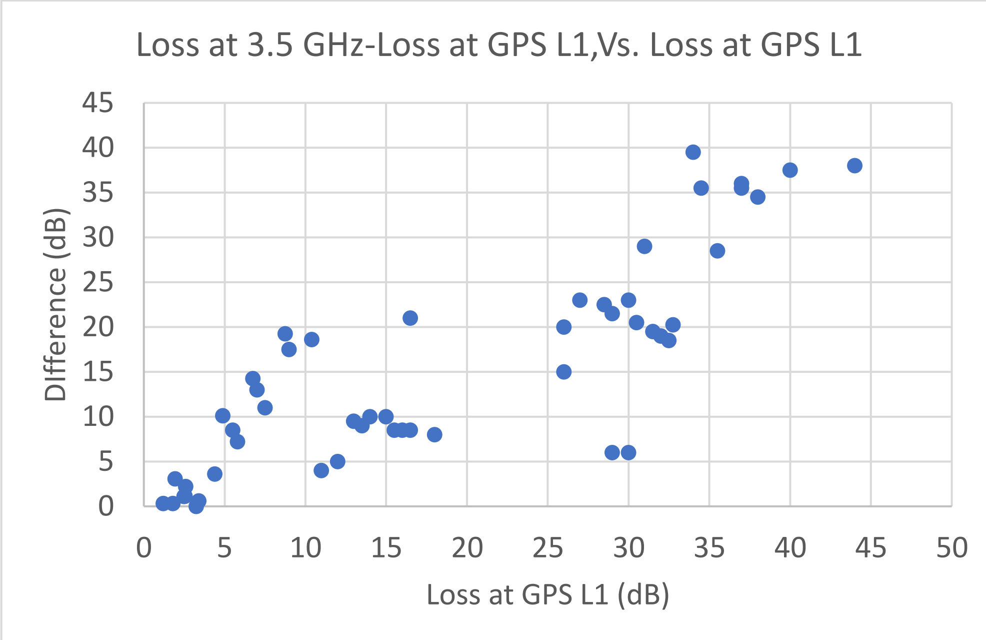

Figure 13: 3.5 GHz loss delta Vs GPS L1 loss for Common Exterior Building materials

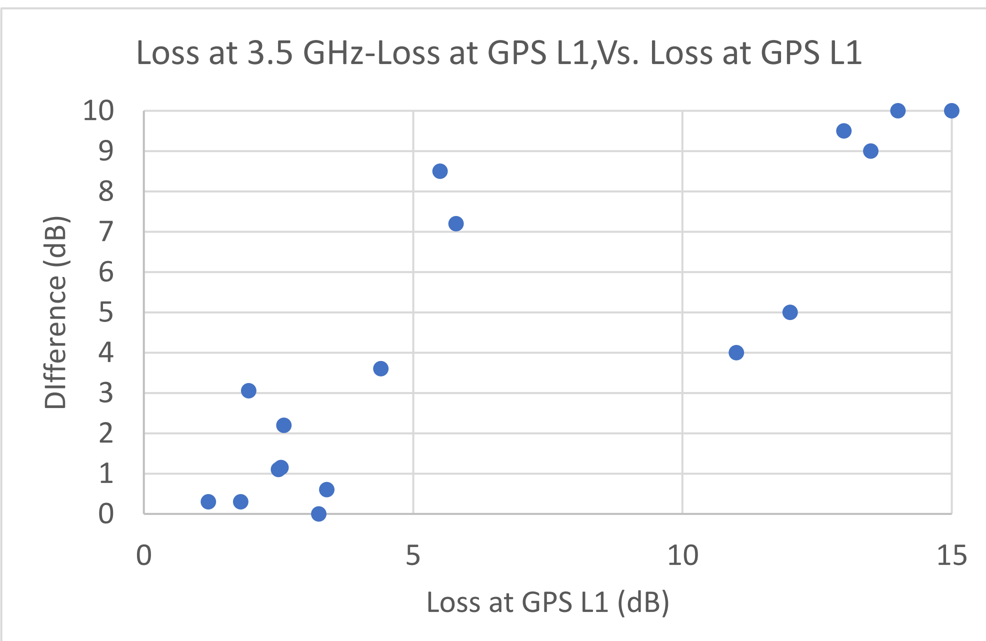

Figure 14: Zoomed in 3.5 GHz loss delta Vs GPS L1 loss for Common

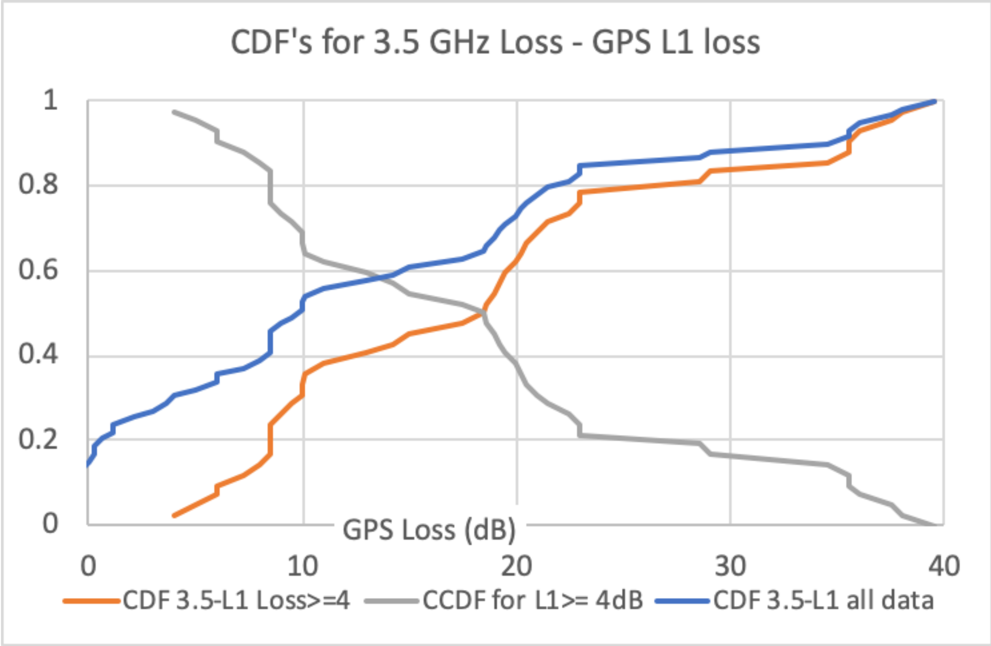

Figure 15: CDFs for L1

For GPS L1 loss >= 4.5 dB 3.5 GHz is at least 3.5 dB higher

4.2 L5 scaling

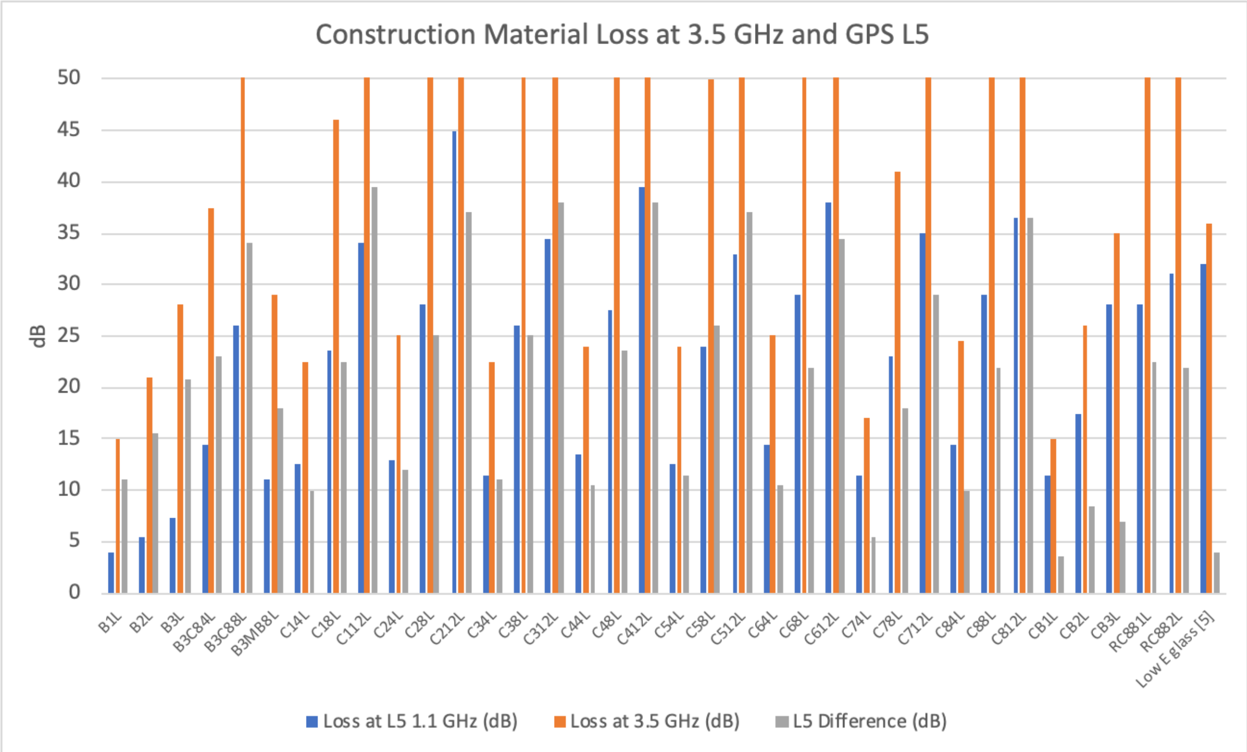

Figure 16: Material losses at 1.575 GNSS L5 and 3.5 GHz. The figure excludes plywood, lumber, standard glass and drywall as these are < 4 dB delta and the L5 and GPS losses are near 0 dB.

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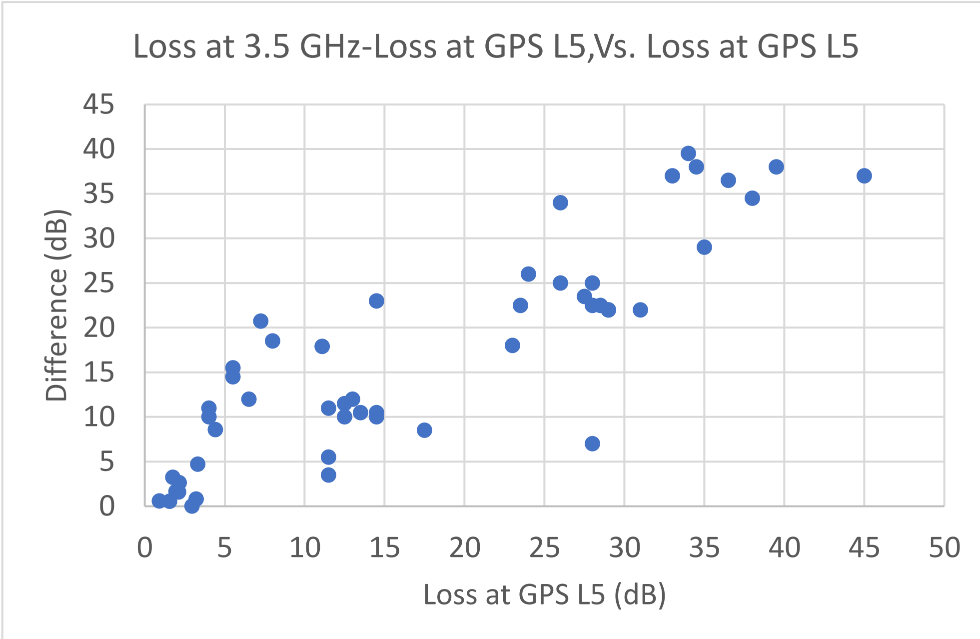

Figure 17: 3.5 GHz loss delta Vs GPS L5 loss for Common

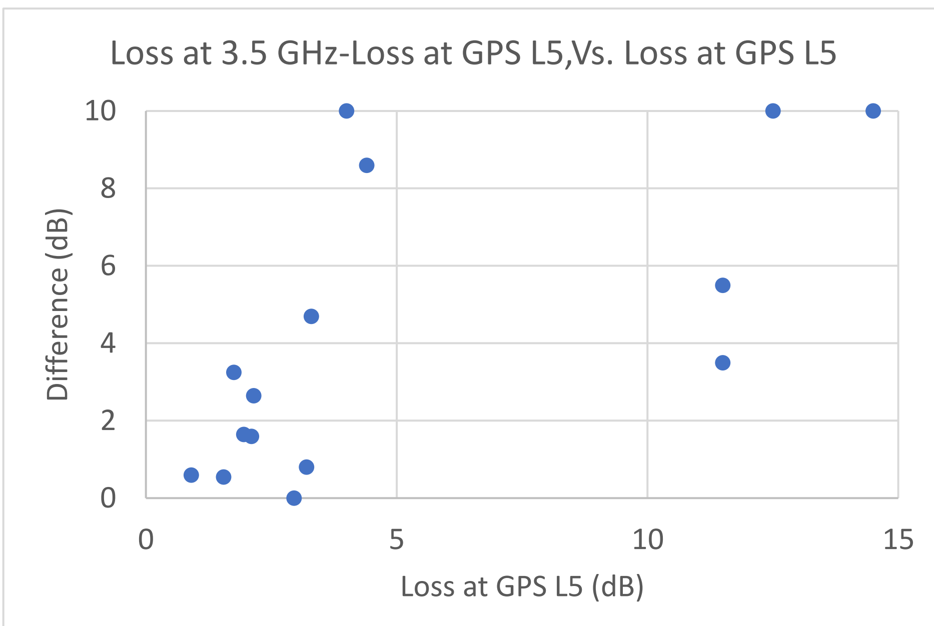

Figure 18: Zoomed in 3.5 GHz loss delta Vs GPS L5 loss for Common

Similar to L1, if the GPS L5 losses are greater than 3.3 dB, 4.5 dB can be added to it to estimate the loss at 3.5 GHz.

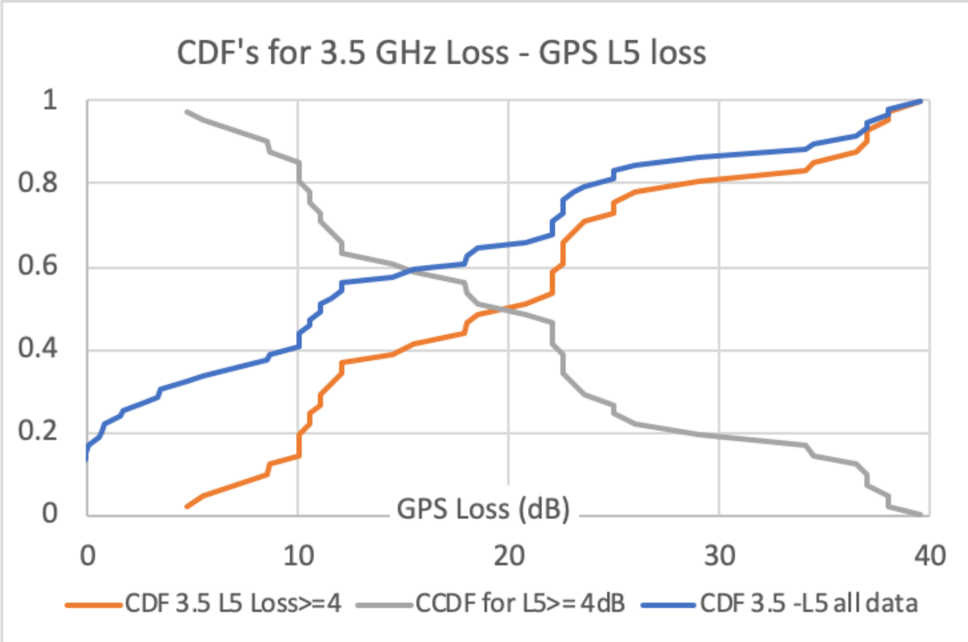

Figure 19: L5 CDFs

For GPS L5 loss >= 3.3 dB 3.5 GHz is at least 4.5 dB higher

5 Use case 2: 6 GHz

5.1 L1 scaling

The measured loss at GNSS L1 and L5 frequencies can be scaled to 6 GHz using the data provided by NIST in [5]. The data was analyzed for absolute loss and for the relative loss from L1 or L5 to 6 GHz. Figure 20 gives a comparison of all the materials measured by NIST excluding very low loss material for L1 and 6 GHz. This is because these materials will bias the difference toward zero although they are rarely if ever used for construction.

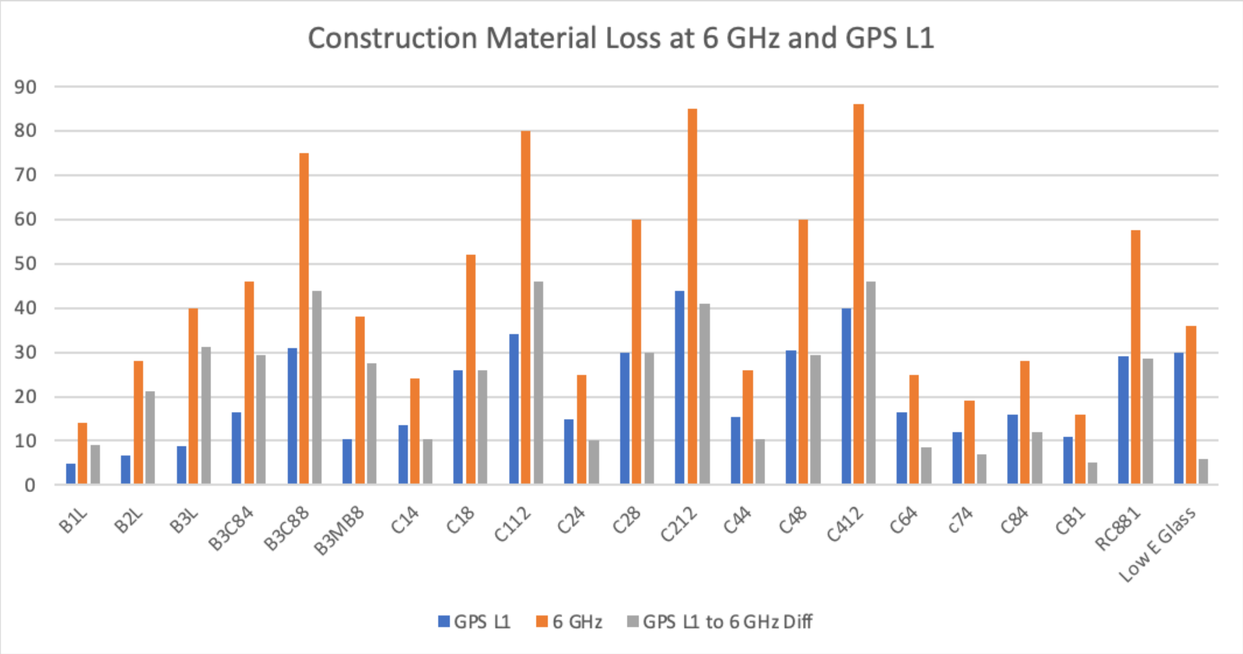

Figure 20: Material losses at 1.575 GNSS L1 and 6 GHz. This figure excludes plywood, lumber, standard glass and drywall as these are < 4 dB delta and the L1 and GPS losses are near 0 dB

The important value is the difference from GPS L1 or L5 to 6 GHz as seen in Figure 21 and Figure 22. This is for all materials except for a re-bar grid as this is not used for construction. What we observe is that for low GPS measured loss, the loss at 6 GHz is also very low, so the difference is negligible. However, when the GPS L1 loss is greater than 4 dB, the difference is at least 4 dB. This provides guidance on how to use the scaling. Specifically, if the GPS L1 loss is >= 4 dB, 4 dB can be added to it to provide an estimate of 6 GHz. Using the method described results in a lower bound for the loss measured using GPS at L1 scaled to 6 GHz. If one were to choose a different threshold then the scale factor would be different accordingly.

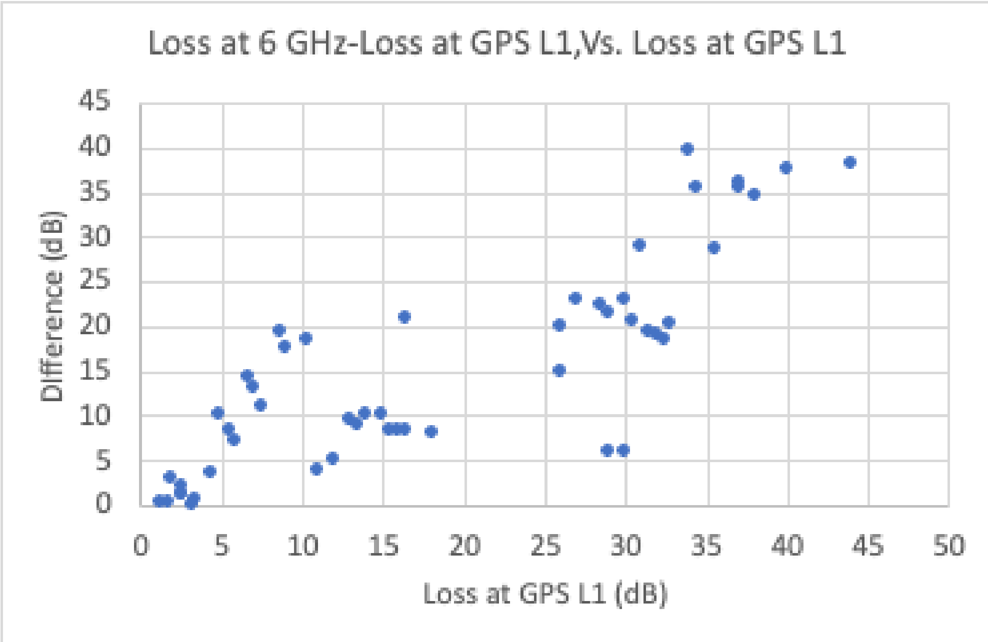

Figure 21: GHz loss delta Vs GPS L1 loss for Common Exterior Building materials

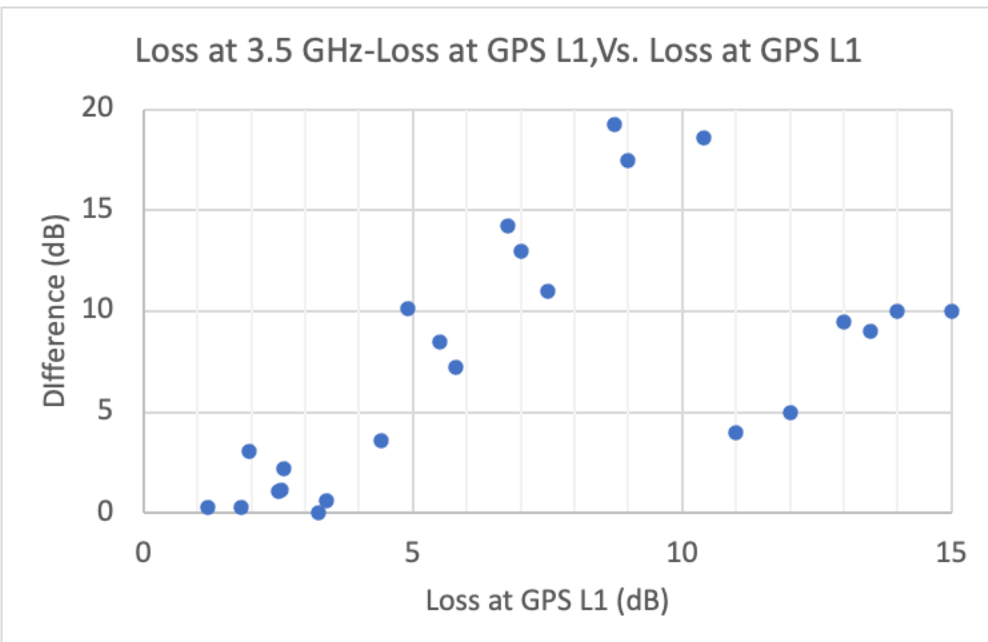

Figure 22: Zoomed in 6 GHz loss delta Vs GPS L1 loss for Common Exterior Building materials

5.2 L5 scaling

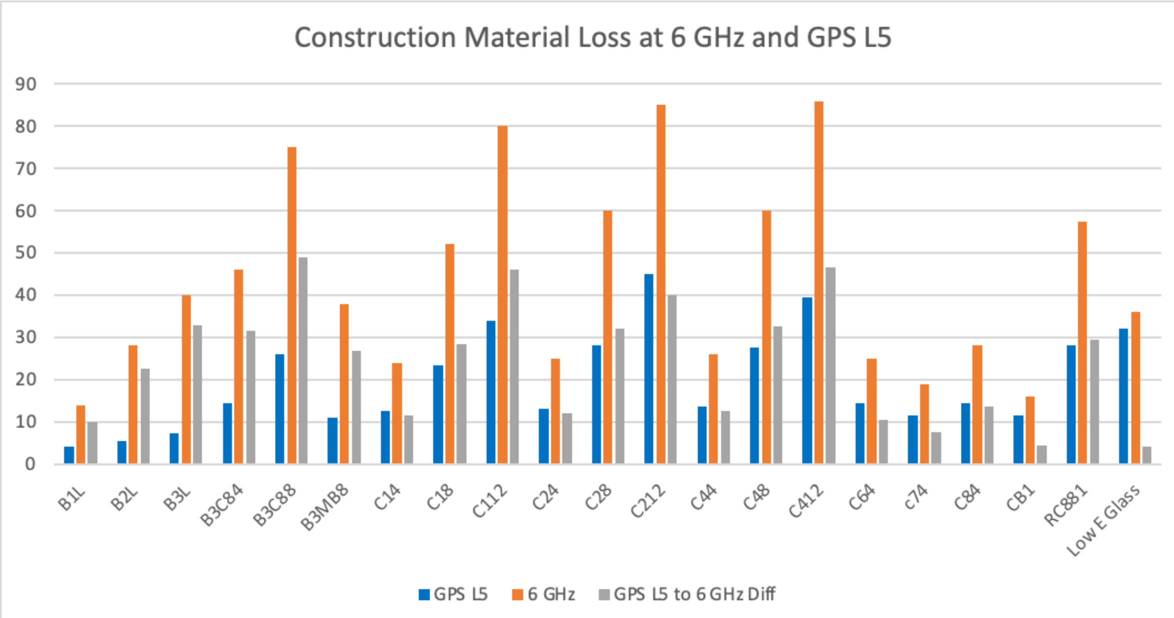

Figure 23: Material losses at 1.176 GNSS L5 and 6 GHz. This excludes plywood, lumber, standard glass and drywall as these are < 4 dB delta and the L5 and GPS losses are near 0 dB

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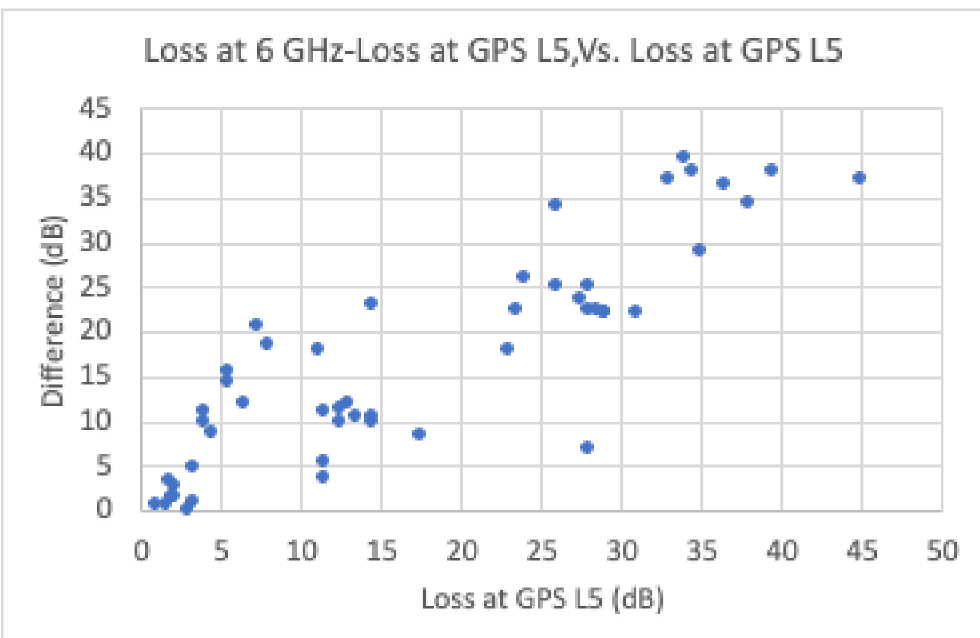

Figure 24: 6 GHz loss delta Vs GPS L5 loss for Common Exterior Building materials

Similar to L1 if the GPS L5 losses are greater than 3.3 dB, 4.5 dB can be added to it to estimate the loss at 6 GHz. Using the method described results in a lower bound for the loss measured using GPS at L5 scaled to 6 GHz.

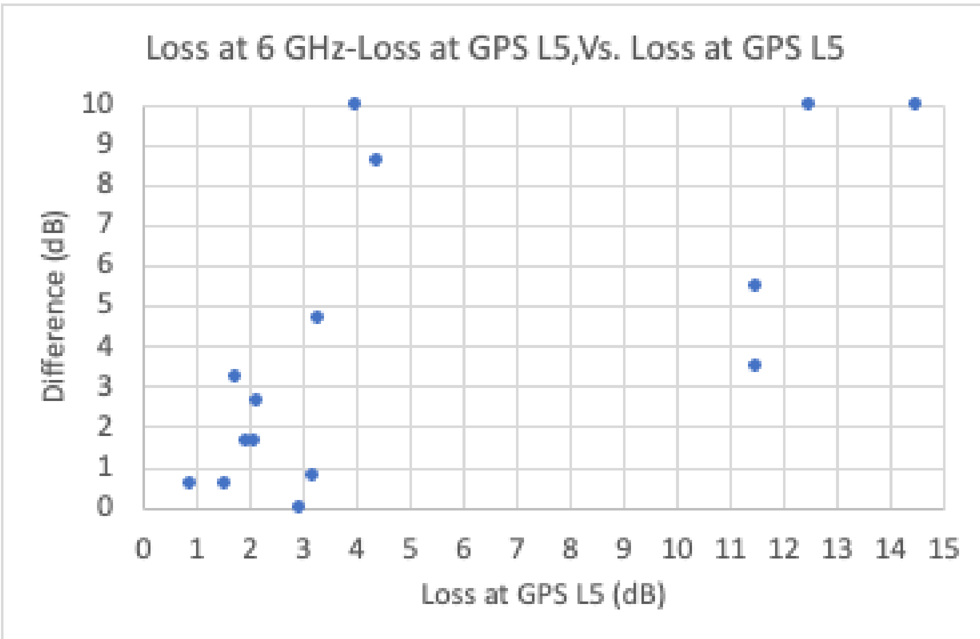

Figure 25: Zoomed in 6 GHz loss delta Vs GPS L5 loss for Common Exterior Building materials

For GPS L5 loss >= 3.3 dB 3.5 GHz is at least 3.5 dB higher so to simplify if losses at GPS L5 are 3 dB or greater then 3 dB can be added to the value to estimate the lower bound loss value at 6 GHz.

6 References

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[5] NIST Construction Automation Program Report No. 3 Electromagnetic Signal Attenuation in Construction Materials, NISTIR 6055, William C. Stone,October 1997

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